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Measurement of Spontaneous Carrier Lifetime from Stimulated Emission Delays in Semiconductor Lasers

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An analysis of the delay between the beginning of the excitation of a semiconductor laser and the onset of stimulated emission is carried out. It justifies the use of these delays as a method of measuring the spontaneous carrier lifetime, even when this lifetime is not the same for all carriers. It is also shown that the lifetime thus measured is the average lifetime of all carriers when the population inversion is at the threshold level.

I. INTRODUCTION

When traps are absent, the delay between the beginning of the excitation pulse and the onset of stimulated emission is governed by the time necessary to achieve threshold population inversion. Konnerth showed that for diode lasers operating at low temperature the delays are proportional to $\ln[I/(I-I_{th})]$ where I and I_{th} are the amplitude of the current pulse and the threshold current, respectively.[1] The proportionality constant is the spontaneous carrier lifetime, assumed to be the same for all carriers.

This behavior of the delays was used to measure the carrier lifetimes in double heterostructure lasers, showing that they are considerably longer than on a p-n junction or single heterostructure lasers.[2] This was attributed to the high level of compensation of the Si-doped GaAs active region. This material shows deeper impurity tails, with the lifetime being excitation dependent—decreasing with increasing excitation level.[3-6] Since this implies that the carrier lifetime is not constant for all carriers, it throws doubt on the validity of the method of measuring the lifetimes using the delays. It also leaves vague the interpretation of the lifetimes thus measured.

The objective of the present paper is to show that in spite of the lifetime not being constant for all states, the time delays are still approximately proportional to $\ln[I/(I-I_{th})]$ and that the constant of proportionality is the carriers at threshold level excitation.

II. TIME DELAY ANALYSIS

The time delay t_d is defined as the time it takes the injected carrier population n to build up a threshold value n_{th} necessary to achieve lasing action. In assuming this threshold value to be independent of the excitation level, we are making some implicit assumptions. First, the presence of trapping centers of the type that cause long delays[7-9] is neglected; these traps, when unsaturated, increase the losses and consequently the value of n_{th}. Since the traps can be saturated by injected electrons during the delay, the value of n_{th} would be smaller for current levels near threshold than at higher injection levels, where the delays are smaller and few traps have time to be saturated. This means that our analysis will not be valid in the so-called long delay region of junction lasers, where the delays are mostly governed by the traps. Another implicit assumption is that, during the delays, the effect of heating on the threshold, can be neglected. In the absence of traps, this can be done with good approximation, since the delays are small ($\sim 10^{-9}$ sec). An exception is the case of double heterostructure lasers, for which the delays are bigger[2] but in this case the threshold current density is much smaller and consequently heating can still be neglected.

The number of injected carriers n, as a function of time, is governed by the following equation:

$$\frac{dn}{dt}=-\frac{n}{\tau(n)}+\frac{I}{e}\ , \tag{1}$$

where I is the injection current; e the charge of the electron; and $\tau(n)$ the average lifetime of the injected carriers when n carriers are present. $\tau(n)$ is defined by

$$\frac{1}{\tau(n)}=\frac{1}{n}\int_{-\infty}^{+\infty}\frac{\rho(E)}{\tau(E)}\left[1+\exp\left(\frac{E-E_F(n)}{kT}\right)\right]^{-1}dE, \tag{2}$$

where (E) is the density of states where the carriers are being injected and $\tau(E)$ the lifetime of states of energy E, kT the Boltzmann factor, and $E_F(n)$ the quasi-Fermi level defined by

$$n=\int_{-\infty}^{+\infty}\rho(E)\{1+\exp[(E-E_F(n))/kT]\}^{-1}dE. \tag{3}$$

The time it takes for the injected population n to achieve the threshold value can be obtained by integrating Eq. (1):

$$t_d=\int_0^{n_{th}}[I/e-n/\tau(n)]^{-1}dn. \tag{4}$$

If prepumping is used to reduce the delays,[2] a similar equation can be used, with the lower limit of integration being substitued by n_0—the prepumped injected population.

Equation (4) cannot be solved analytically except for particular functional dependences of $\tau(n)$. In order to solve approximately, let us add and subtract $n/\tau(n_{th})$ inside the bracket:

$$t_d=\int_0^{n_{th}}\left[\frac{I}{e}-\frac{n}{\tau(n_{th})}+n\left(\frac{1}{\tau(n_{th})}-\frac{1}{\tau(n)}\right)\right]^{-1}dn. \tag{5}$$

Let us at this point define the threshold current I_{th} as the current necessary to achieve n_{th} at $t=\infty$ (heating still neglected):

$$I_{th}=n_{th}e/\tau(n_{th}). \tag{6}$$

Except for currents very near threshold,

$$n\left(\frac{1}{\tau(n_{th})}-\frac{1}{\tau(n)}\right)\ll\frac{I}{e}-\frac{n}{\tau(n_{th})}\ , \tag{7}$$

since $\tau(n)$ only differs significantly from $\tau(n_{th})$ when n is very small.

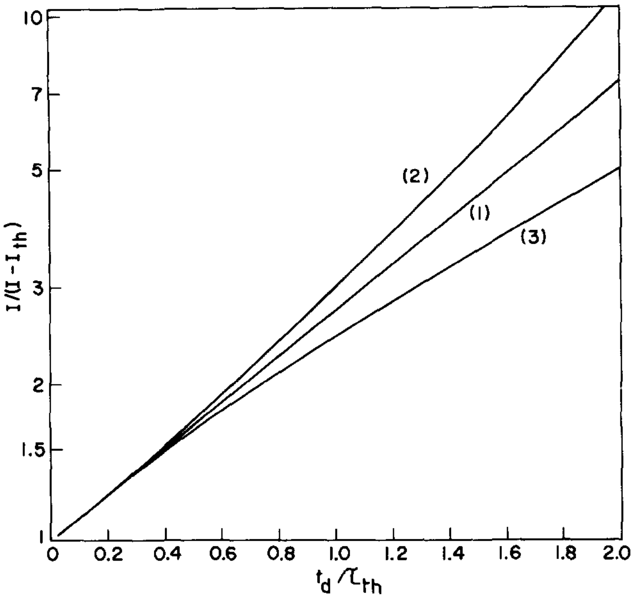

FIG. 1. Calculated time delays as a function of $\ln[I/(I-I_{th})]$ for $\tau=\tau_{th}(n/n_{th})^{\alpha}$. Curve (1) assumes $\alpha=0$ so τ is a constant. Curve (2) assumes $\alpha=-\frac{1}{2}$, a stronger dependence of τ on n than that occuring in the laser, but in the same direction. Curve (3) assumes $\alpha=\frac{1}{2}$, making the dependence of τ on n opposite from the real one. The experimental curve should fall between curves (1) and (2).

This allows us to approximate Eq. (5) to

$$t_d=\left\{\int_0^{n_{th}}[I/e-n/\tau(n_{th})]^{-1}\,dn\right\}-t_1\;, \tag{8}$$

where

$$t_1=\int_0^{n_{th}} n\left(\frac{1}{\tau(n_{th})}-\frac{1}{\tau(n)}\right)\left(\frac{I}{e}-\frac{n}{\tau(n_{th})}\right)^{-2}dn \tag{9}$$

is a small correction except very near threshold and gets rapidly smaller as the current I is increased.

Integrating the first term of Eq. (8) and using Eq. (6), we get

$$t_d\simeq\tau(n_{th})\ln[I/(I-I_{th})]-t_1. \tag{10}$$

So, in spite of the fact that the lifetime is not constant during the delay, the delays are still proportional to $\ln[I/(I-I_{th})]$, except for a correction t_1 that is significant only very near threshold. The proportionality constant is the average lifetime at threshold level. The lifetime of the injected carriers before threshold is reached is larger than at threshold because deeper states have smaller recombination probability than shallower ones.[3-6] This leads to $t_1>0$, so the small error introduced by it is to turn the measured lifetime *smaller* than $\tau(n_{th})$. It is also worth noting that the region near threshold where t_1 can be significant is also the region where even small experimental errors in the determination of I_{th} and the delays, due to heating and irregularities on the current pulses, cause the experimental results to be unreliable anyway.

III. TIME DELAY CALCULATION

In order to estimate the error introduced by the approximations used in Sec. II., Eq. (4) was integrated in a computer for several assumed dependences of $\tau(n)$. The results of these calculations are shown in Fig. (1).

If $\tau(n)=\tau_{th}$, a constant Eq. (10) is exact with $t_1=0$ over the whole range and t_d is proportional to the $\ln[I/(I-I_{th})]$. This is shown in curve (1).

If we assume $\tau(n)=\tau_{th}(n/n_{th})^{-1/2}$, in which $\tau(n)$ increases more rapidly than in reality as the excitation is decreased, a small deviation toward smaller delays occurs. For currents near threshold (upper part of the curve), the value of t_1 measured as the deviation of curve (2) from curve (1) can become significant (of the order of 15%). This value, and consequently the error in the determination of τ_{th} is quite small for larger currents. The exact dependence of $\tau(n)$ is not known but should be slower than $n^{-1/2}$, so that the experimental curve should be between curves (1) and (2), with an even smaller error.

For completeness, curve (3) corresponding to $\tau(n)=\tau_{th}(n/n_{th})^{1/2}$ is also shown where the lifetime increases with the injection level, opposite to the real one. In this case the error would be toward a larger $\tau(n_{th})$ $(t_1>0)$.

IV. CONCLUSIONS

The present calculations show that the delay between the beginning of the excitation of a laser and the onset of the spontaneous emission can be used to measure the spontaneous carrier lifetime even when this lifetime is not the same for all states. The lifetime thus measured is the average lifetime of all states at threshold population inversion level. Physically this can be understood from the fact that even if the injection is varied over a wide range, the same states are being filled up to the onset of stimulated emission. When deeper states have *longer* lifetimes, the value of the measured τ is slightly shorter than $\tau(n_{th})$. This apparently surprising result can be understood by considering that when the inversion is small, less injected carriers recombine than if all states had $\tau=\tau(n_{th})$, thus leading to a faster filling of states and shorter delays.

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